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*Effect of Hole Size on Pressure Measurements  
Made With a Flat-Plate Dynamic-Head Probe*

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JET PROPULSION LABORATORY  
CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA

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Made With a Flat-Plate Dynamic-Head Probe***

*George I. Jaivin*

A handwritten signature in dark ink, appearing to read 'D. R. Bartz', is written over a horizontal line.

D. R. Bartz, Chief  
Propulsion Research Section

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CALIFORNIA INSTITUTE OF TECHNOLOGY  
PASADENA, CALIFORNIA**

June 15, 1964

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## CONTENTS

<b>I. Introduction</b>	1
<b>II. Description of Problem</b>	2
A. Dynamic-Head Probe	2
B. Simulation of LeClerc Pressure Distribution	2
C. Analysis of the Problem	4
<b>III. Experimental Procedures</b>	6
A. Method of Attack	6
B. Experimental Apparatus	7
1. Dynamic-Head Probe Plates	7
2. Thrust Measuring Balance	7
3. Miscellaneous Apparatus	7
<b>IV. Experimental Results</b>	7
A. Presentation of Data	7
B. Analysis of Data	8
<b>V. Summary</b>	11
<b>Nomenclature</b>	12
<b>References</b>	12

## TABLES

1. Flat-plate pressure distributions as computed by LeClerc and as determined by Rupe for the impingement of a laminar, near-uniform velocity profile free liquid jet	4
2. Pressure distribution produced by a laminar, uniform velocity profile jet impinging on a flat plate	9
3. Pressure distribution produced by a fully developed turbulent velocity profile jet impinging on a flat plate	9
4. Reaction force produced by jet impingement on a flat plate as determined by the thrust balance and by integration of net measured pressure force on the plate	11

## FIGURES

1. Details of flat-plate dynamic-head probe gage assemblies . . . . .	2
2. Laminar, uniform velocity profile jet-flow fixtures . . . . .	3
3. Pressure distribution produced by a laminar, near-uniform velocity profile jet impinging on a flat plate . . . . .	4
4. Visual characteristics of jets formed by sharp-edge orifices . . . . .	5
5. Pressure distribution produced by a laminar, uniform velocity profile jet impinging on a flat plate . . . . .	8
6. Pressure distribution produced by a fully developed turbulent velocity profile jet impinging on a flat plate . . . . .	10

## ABSTRACT

25772

The dynamic-head probe, a device for evaluating the properties of free liquid jets, produced anomalous results when used to evaluate the characteristics of a laminar, uniform velocity profile jet. A comparison of the integrated pressure force on the probe with the measured thrust indicated inaccurate pressure measurements to be the cause. An investigation of the effect of the hole size used in the probe showed this factor to be significant in affecting the accuracy of the pressure measurements. A ratio of the probe hole diameter to the jet diameter of 0.04 was found sufficient to eliminate probe hole effects and to produce a good correlation of experimental and theoretical pressure data.

*Author*

## I. INTRODUCTION

The importance of accurate pressure measurements is patently acknowledged by all who are engaged in the empirical evaluation of physical phenomena. The degree to which the pressure measurement in question is truly representative of the actual value of this parameter in a given test environment is dependent upon a number of factors. For systems involving flowing fluids, for instance, the measurement of static pressure by means of a small static hole located on a probe plate or boundary wall has been shown (Ref. 1-4) to be affected by the size, shape, depth, orientation, and condition of the hole used. The local shearing stress in the vicinity of the hole, the density and viscosity of the fluid, and the hole size have been shown by Shaw (Ref. 1) and others to be significant parameters in the correlation of pressure measurement errors. The determination of fluctuating pressure components in a flow system cannot be successfully accomplished without a detailed consideration of the flow in the connecting pressure lines and the dynamic characteristics of the pressure measuring device (Ref. 2). Thus, the veracity of an experimental pressure determination must, in every case, be judged against the error-inducing conditions existing when the measurement was made.

Rupe (Ref. 5) reported the fabrication of a dynamic-head probe for evaluating the hydrodynamic properties of free liquid jets. This probe has proven to be a valuable tool in the characterization of such flows since it permits comparisons of unknown jet velocity profiles to be readily made. Moreover, a suitably designed probe of this type can provide useful data concerning the intensity of turbulence within a free liquid jet. In a subsequent report (Ref. 6), Rupe presented the results obtained when the probe was used to investigate the characteristics of certain reference jet configurations. Critical examination of the data presented therein revealed a discrepancy between a hypothetical pressure distribution obtained by LeClerc (Ref. 7) and the experimental data obtained from a flow geometry which closely modeled the theoretical case. It is felt that the differences noted by Rupe may have resulted from errors in the pressure measurements caused by the relatively large static hole size of the probe used in the experiments. In order to test this premise, an empirical evaluation of the effect of probe hole size upon the resulting pressure distribution was undertaken and the results of this investigation are presented herein.

## II. DESCRIPTION OF PROBLEM

### A. Dynamic-Head Probe

The dynamic-head probe, as originally conceived by Rupe, was built in order to evaluate the dynamic properties of a free liquid jet. It was assumed that a unique correlation exists between the pressure distribution produced by the impingement of a free jet upon a flat plate and the velocity profile of the jet. The probe design was based on locating a small hole in the center of a flat plate. The hole, which served as the probe, was the only opening to a cavity bounded on one side by a pressure sensing element (Fig. 1a). In relation to the stream diameter the plate was large and the hole was small, such that the flow configuration produced by the impingement of the stream on the plate did not change as the probe was moved from point to point in the pressure field.

It was intended that the probe be used, not only to measure the time-averaged values of the local pressure, but also to determine the pressure fluctuations associated with stream turbulence. In order to accomplish the latter purpose, an extensive development effort was undertaken by Rupe before a suitable probe design was found which was capable of meeting the experimental objectives. The final design consisted of a 0.020-in.-D hole through a flat

plate which opened into a near-minimum-volume cavity. Probe hole diameters of either 0.019 or 0.022 in. were thereupon established as standard sizes for all subsequent work with the dynamic-head probe, and correspond to the probe sizes used to obtain the data given in Ref. 6.

### B. Simulation of LeClerc Pressure Distribution

LeClerc (Ref. 7), by means of an electrical analogue technique, determined the potential flow solution of a hypothetical, uniform velocity profile, free cylindrical jet impinging on a flat plate and, as a consequence, was able to compute the theoretical pressure distribution on the plate. The impingement of a laminar, uniform velocity profile free liquid jet upon a flat plate bears a very strong similarity to the theoretical model solved by LeClerc, since viscosity does not play a significant role in the flow development in this instance. Rupe built a flow fixture (Fig. 2a) which was designed to produce such a jet and then measured the pressure distribution on a flat plate produced by the jet's impingement upon it. The results, as reported in Ref. 6, are shown in Fig. 3. The ordinate  $P/P_c$  is the ratio of the measured pressure on the plate to the centerline stagnation pressure that would have been produced by a jet having the same flow rate but a

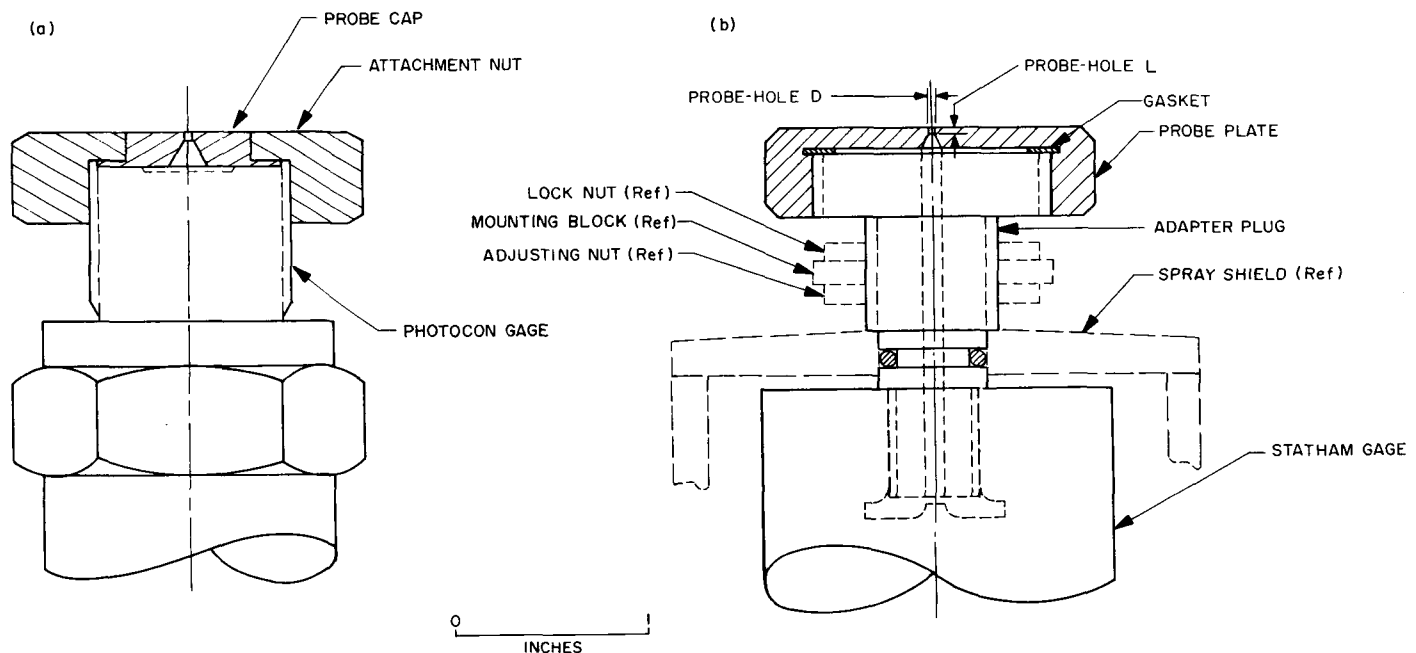


Fig. 1. Details of flat-plate dynamic-head probe gage assemblies:  
(a) Used by Rupe (Ref. 5); (b) Used in this investigation

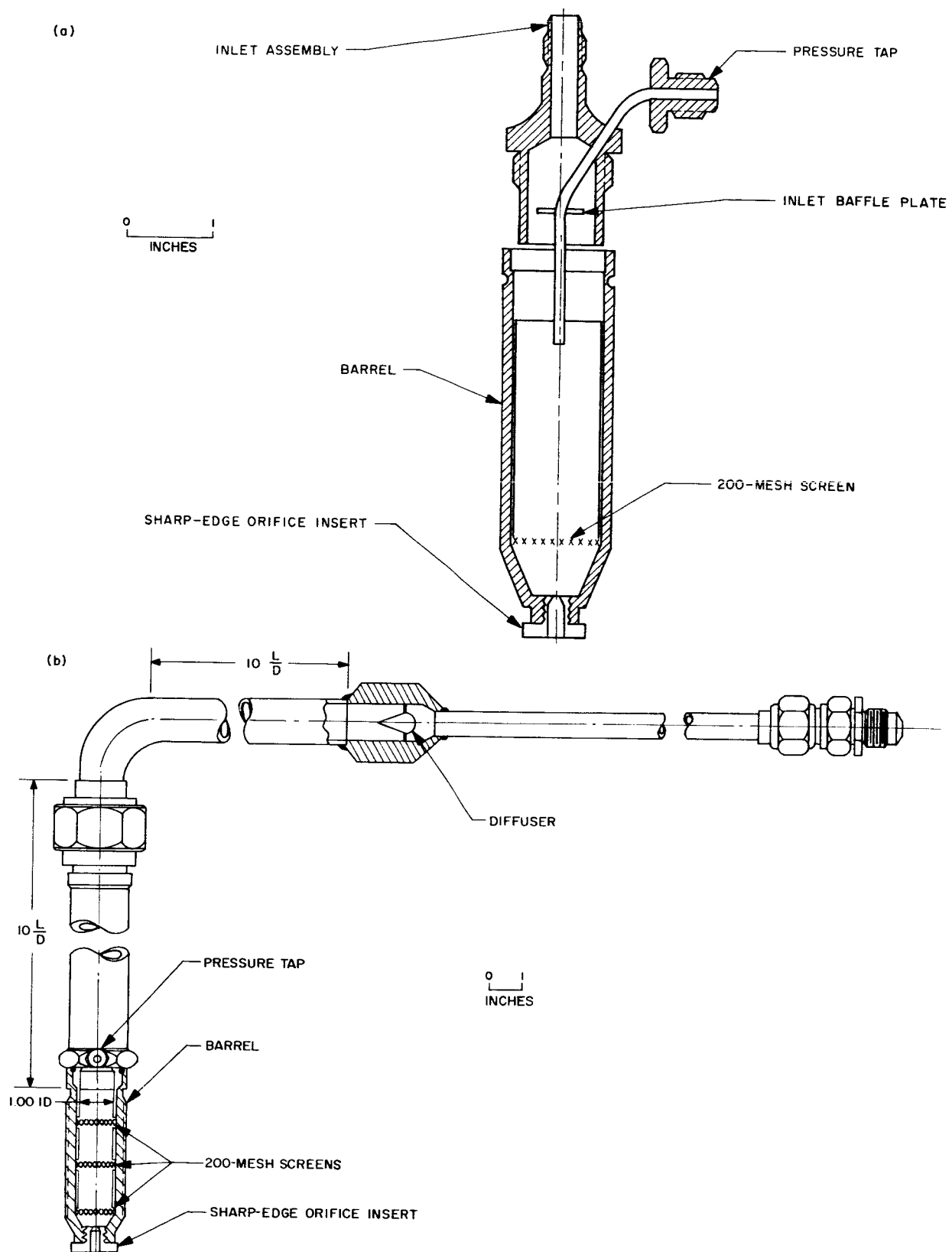
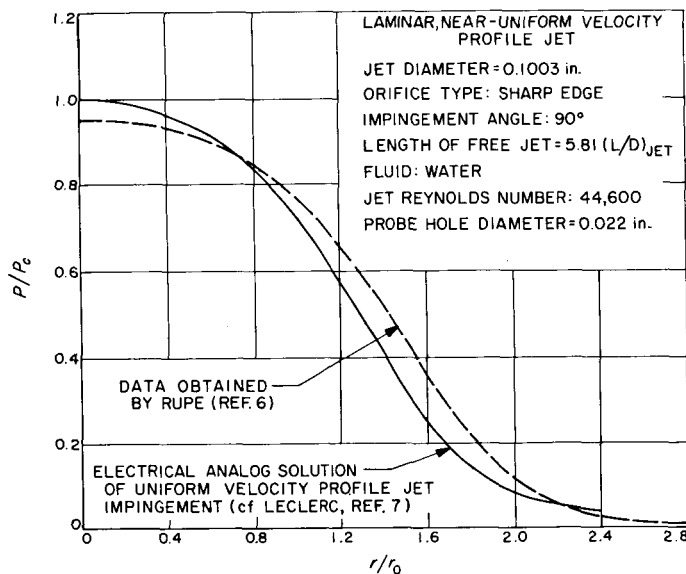


Fig. 2. Laminar, uniform velocity profile jet-flow fixtures: (a) Used by Rupe (Ref. 5); (b) Used in this investigation



**Fig. 3. Pressure distribution produced by a laminar, near-uniform velocity profile jet impinging on a flat plate**

uniform velocity profile. The abscissa  $r/r_0$  is the ratio of the radius between the point of measurement and the centerline of the stream to the radius of the jet. The pressure distribution inferred by LeClerc is also included for comparison. A 5% discrepancy is noted between the two curves at the centerline of the jet and larger differences are observed for values of  $r/r_0 > 0.8$ . These data are also presented in tabular form in Table 1. No definitive evidence was presented by Rupe to explain the noted differences, and it was concluded by him that "the distribution is either real and quite stable or that one or more of the constants utilized in obtaining the pressure ratio is in error."

### C. Analysis of the Problem

Because of the care taken in the acquisition of the experimental data reported in Ref. 6, it is unlikely that a significant error can be attributed to gross experimental inaccuracies. A more likely reason for the observed differences is thought to be the hole size used in the dynamic-head probe. In general, the presence of a hole in a surface inevitably disturbs the flow in the boundary layer close to the hole and, thus, the pressure measured is usually not the true static pressure. The precise details of the flow disturbances associated with a static hole are not fully understood, but previous work (Ref. 1, 3) has shown that some fluid very close to the wall in the approaching boundary layer actually enters the hole and circulates as part of an eddy, or system of eddies, before rejoining the main flow at the lateral edges of the hole.

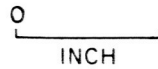
**Table 1. Flat-plate pressure distributions as computed by LeClerc and as determined by Rupe for the impingement of a laminar, near-uniform velocity profile free liquid jet**

$r/r_0$	$P/P_c$	
	LeClerc pressure distribution	Laminar, uniform velocity profile jet pressure distribution <sup>a</sup>
0	1.000	0.952
0.199	0.988	0.949
0.399	0.962	0.933
0.598	0.916	0.901
0.798	0.835	0.848
0.997	0.723	0.767
1.196	0.580	0.656
1.396	0.415	0.512
1.595	0.250	0.358
1.795	0.133	0.216
1.994	0.078	0.115
2.193	0.051	0.060
2.393		0.032
2.792		0.013
3.190		0.008
3.988		0.004

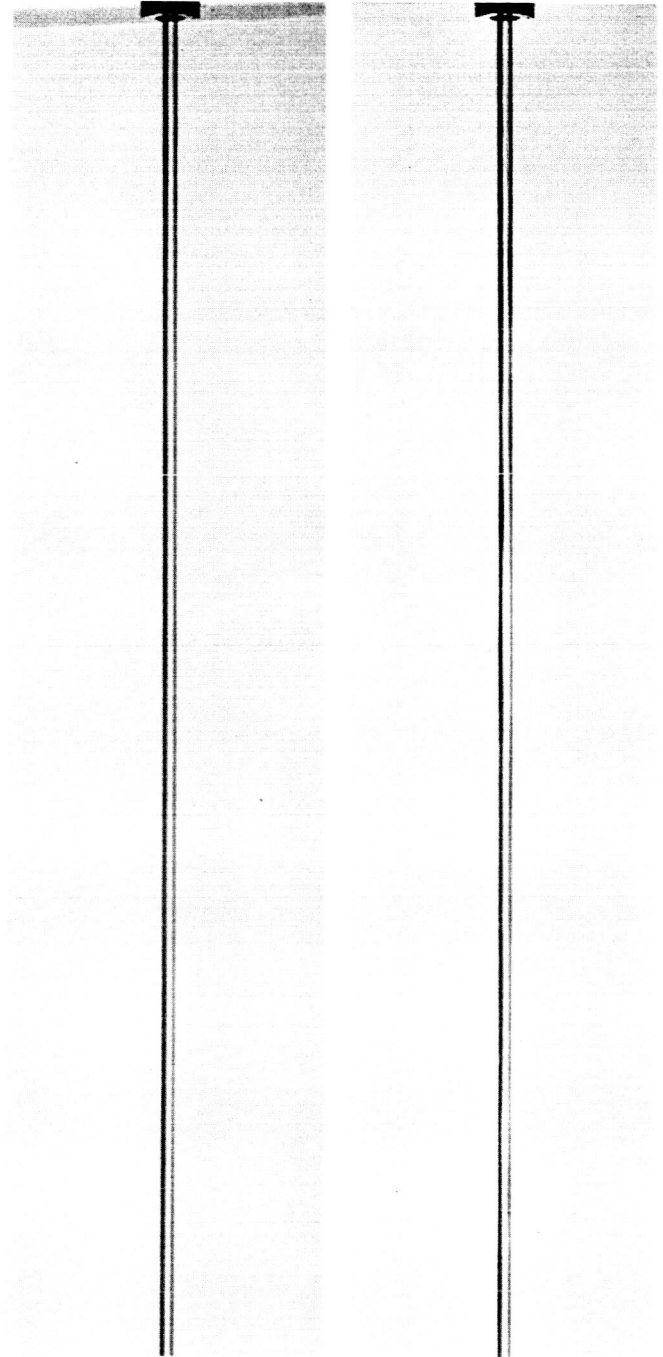
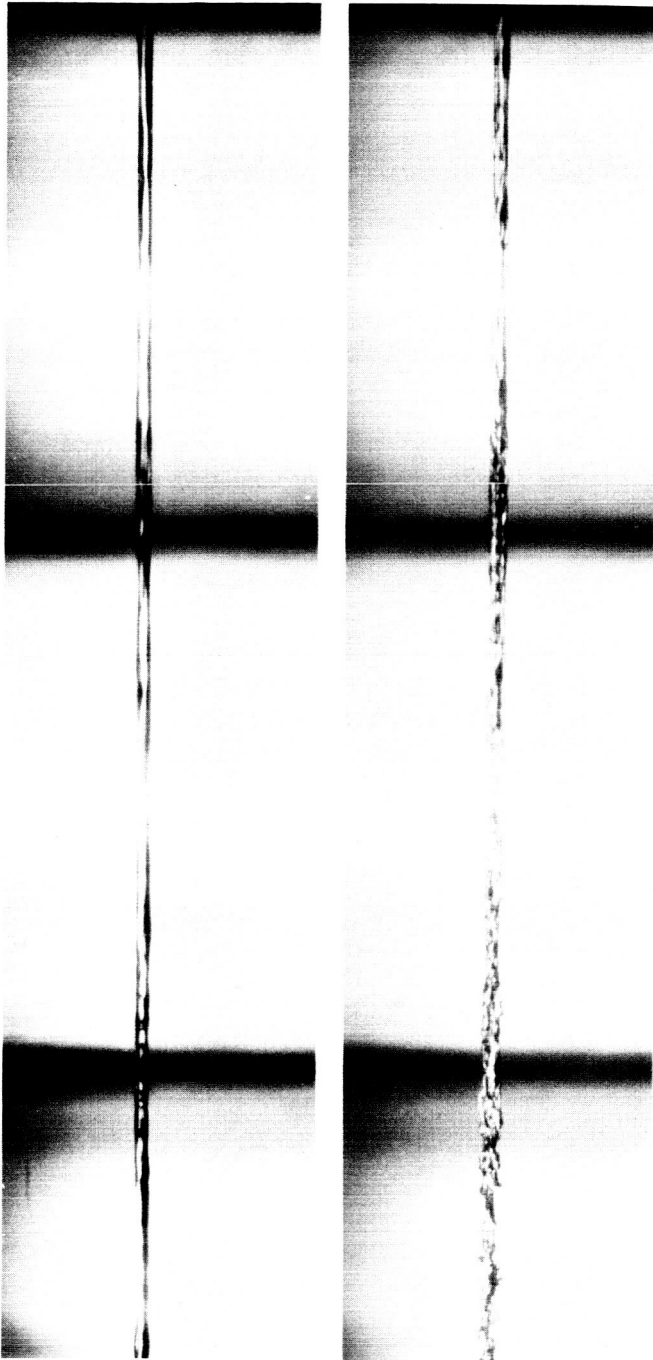
<sup>a</sup>Jet diameter = 0.1003 in.  
 Orifice diameter = 0.1273 in.  
 Orifice: sharp edge  
 Impingement angle = 90°  
 Length of free jet = 5.81 (L/D)<sub>jet</sub>  
 Fluid: water  
 Jet Reynolds number: 44,600  
 Probe hole diameter = 0.022 in.  
 (Data originally presented in Ref. 6)

The static pressure error can be considered to be made up of three factors: (1) the increase in the static pressure in the hole resulting from the curvature of the flow streamlines in the immediate vicinity of the hole, (2) the pressure distribution within the hole due to the asymmetry of the flow in that region, and (3) a pitot effect associated with the stagnation of the approaching flow just inside the hole on the downstream edge. There have been many investigations of the errors associated with the size of the static pressure hole, and all have indicated that the factors mentioned above decrease in significance as the hole size decreases such that the error in the pressure measurement goes to zero as the hole diameter approaches zero.

(a) JET DIAMETER = 0.1003 in.  
ORIFICE: SHARP EDGE  
FLUID: WATER



(b) JET DIAMETER = 0.1176 in.  
ORIFICE: SHARP EDGE  
FLUID: WATER



$V_{JET} = 74.5$  ft./sec  
 $(N_R)_{JET} = 61,800$

$V_{JET} = 149.1$  ft./sec  
 $(N_R)_{JET} = 123,900$

$V_{JET} = 50.0$  ft./sec  
 $(N_R)_{JET} = 48,600$

$V_{JET} = 77.1$  ft./sec  
 $(N_R)_{JET} = 75,100$

Fig. 4. Visual characteristics of jets formed by sharp-edge orifices: (a) Used by Rupe (Ref. 6); (b) Used in this investigation

In the case in point, the diameter of the probe hole used to evaluate the stream was approximately 20% as large as the diameter of the jet. While no available earlier work clearly indicates the magnitude of the error to be expected due to this factor, it was felt that sufficient evidence is to be found in the literature to justify a closer examination of the data in light of the above mentioned possible sources of error.

Examination of the visual properties of the jet used by Rupe to model the LeClerc jet (Fig. 4a) indicates a slightly disturbed stream surface. While conclusions

drawn from such evidence are obviously qualitative in nature, it would appear that the supposedly *laminar* jet used was actually experiencing some flow perturbation caused, perhaps, by the supply system. As observed in Ref. 6: "It is . . . absolutely essential that the reservoir from which the jet discharges be completely quiescent and that there be no mechanical disturbance of the system itself. These processes become extremely important in jets of low viscosity formed from short orifices, where there are no dissipative mechanisms available to mask or minimize such disturbances." A possible additional factor contributing to the differences noted may be traceable to this cause.

### III. EXPERIMENTAL PROCEDURES

#### A. Method of Attack

In order to evaluate the effect of probe hole size on the resulting pressure distribution caused by the impingement of a free liquid jet on the dynamic-head probe, three new probe plates were built. The hole diameters were 0.019, 0.004, and 0.0016 in. The 0.019-in.-D probe was intended to be used as a reference size in order to establish a point of comparison between the new data and that presented in Ref. 6. The other two sizes were arbitrarily chosen to represent hole diameters markedly dissimilar from those previously used. The 0.0016-in. diameter represented a practical limit to the hole size that could be produced without the use of specialized manufacturing procedures.

In addition to the direct comparison indicated above, it was felt that a means other than noting the departure from a theoretical pressure curve would be desirable in evaluating the effect of the hole size upon the experimental data. To this end it was recognized that a free liquid jet impinging normally upon a flat plate imparts a force to the plate whose magnitude is equal to the time rate of change of the momentum of the jet. Since the net integrated pressure force acting on the plate is also identically equal to the reaction force, independent experimental measurements of both the pressure distribution on the surface of the probe and the force exerted on the plate by the impinging jet could be used to determine the accuracy of the empirical pressure data. Note that

the pressure force on the plate is given by the integral relation

$$2\pi \int_0^R Pr dr$$

The value of this integral may be readily found by means of graphical integration after computing and plotting a curve of  $Pr$  versus  $r$  for a given pressure distribution as measured on the surface of the probe plate. The area under this curve, as determined by a planimeter, is therefore directly proportional to the pressure force on the plate. Such a scheme was employed to evaluate the data obtained by the use of the three new probes.

As noted earlier, the possibility of upstream disturbances affecting the jet, and hence the ultimate accuracy of the pressure distributions as reported in Ref. 6, did exist. In an attempt to improve the jet characteristics a baffle plate which was in the original flow fixture (Fig. 2a) was removed. A 10-L/D extension followed by a 3-in.-radius turn and another 10-L/D straight section (Fig. 2b) were added to the original orifice barrel assembly. The resulting change in the visual characteristics of the jet is shown in Fig. 4b. The jet appeared perfectly smooth at all velocities up to approximately 100 ft/sec. A slight ruffling of the surface began to be evident at approximately that velocity, presumably as a result of aerodynamic interactions at the surface and/or disturbances arising in the upstream system as the mean flow velocity was increased.

## B. Experimental Apparatus

### 1. Dynamic-Head Probe Plates

Three flat-plate probes were built in accordance with the details set forth in Ref. 5. The new probe plates were made in one piece (Fig. 1b) in order to circumvent an experimental difficulty often encountered with the two-piece probe. It was found, with the old probe design, that a slight misalignment of the two pieces caused a flow separation on the surface of the probe which seemed to be associated with the negative gage pressure readings that were often observed at the extremities of the pressure field. The surfaces of the new probes were carefully lapped to produce a smooth finish and subsequently no instance of negative pressure readings was observed.

In order to improve the stability of the pressure monitoring system, a Statham pressure transducer Model P24-50A-100 (0 to 50 psig) replaced the Photocon system previously used by Rupe. Although this resulted in a somewhat degraded response characteristic of the overall system, particularly for the probes with the smallest holes, the configuration indicated in Fig. 1b yielded typical response times of 1.0 sec.

The lengths of the holes in the three probe plates were 0.005, 0.003, and 0.002 in. for the 0.019-, 0.004-, and 0.0016-in.-D probes, respectively. As indicated in Ref. 5 these lengths were achieved by counterboring the under side of the probe plate. In the case of the smallest two probes, however, the drilling of the holes was done *after*

the counterboring operation since it was not possible to drill very long L/D holes having the small diameters desired.

### 2. Thrust Measuring Balance

The thrust produced by the impingement of a jet on a plate was measured in a straightforward manner by mounting the plate on one side of a laboratory pan balance. The jet was made to impinge on the plate and the reaction force produced was then determined directly by loading the other side of the pan balance with dead weights until equilibrium balance was restored. An appropriately shaped shield was used to protect the scale from the liquid leaving the probe surface. Force readings could easily be made to the nearest 0.1 g with an estimated accuracy of  $\pm 0.05$  g.

### 3. Miscellaneous Apparatus

Volume flow rates were determined by a Waugh Model FL-8S turbine flow meter. The output of the turbine meter was monitored by a Hewlett-Packard EPUT counter. The accuracy of the flow-rate measurement is estimated to be  $\pm 0.4\%$ .

The traveling microscope technique as described in Ref. 6 was used to determine the diameter of the jet. Because of the improvement noted in the stability of the jet the slight instabilities in the jet boundary observed by Rupe were not apparent. The measurements were reproducible to within  $\pm 0.0001$  in.

## IV. EXPERIMENTAL RESULTS

### A. Presentation of Data

Figure 5 illustrates the results obtained when the 0.019-, 0.004-, and the 0.0016-in.-D probes were used to measure the pressure distributions resulting from the impingement of a laminar, uniform velocity profile jet upon a flat plate. Also included for comparative purposes are the results obtained by Rupe (Ref. 6 or Fig. 3), as well as the theoretical pressure distribution computed by LeClerc. The data have been non-dimensionalized as shown to facilitate data analysis. These data are also presented in tabular form in Table 2.

Figure 6 shows the pressure distributions on a flat plate, as measured with the 0.019- and 0.0016-in.-D probes, produced by the impingement of a fully developed turbulent velocity profile free liquid jet. The LeClerc pressure distribution is also given. A tabulation of these data can also be found in Table 3.

A comparison between the measured reaction force resulting from the jet impingement on the plate and the net integrated pressure force on the probe surface is made in Table 4 for the several probe sizes and jet types

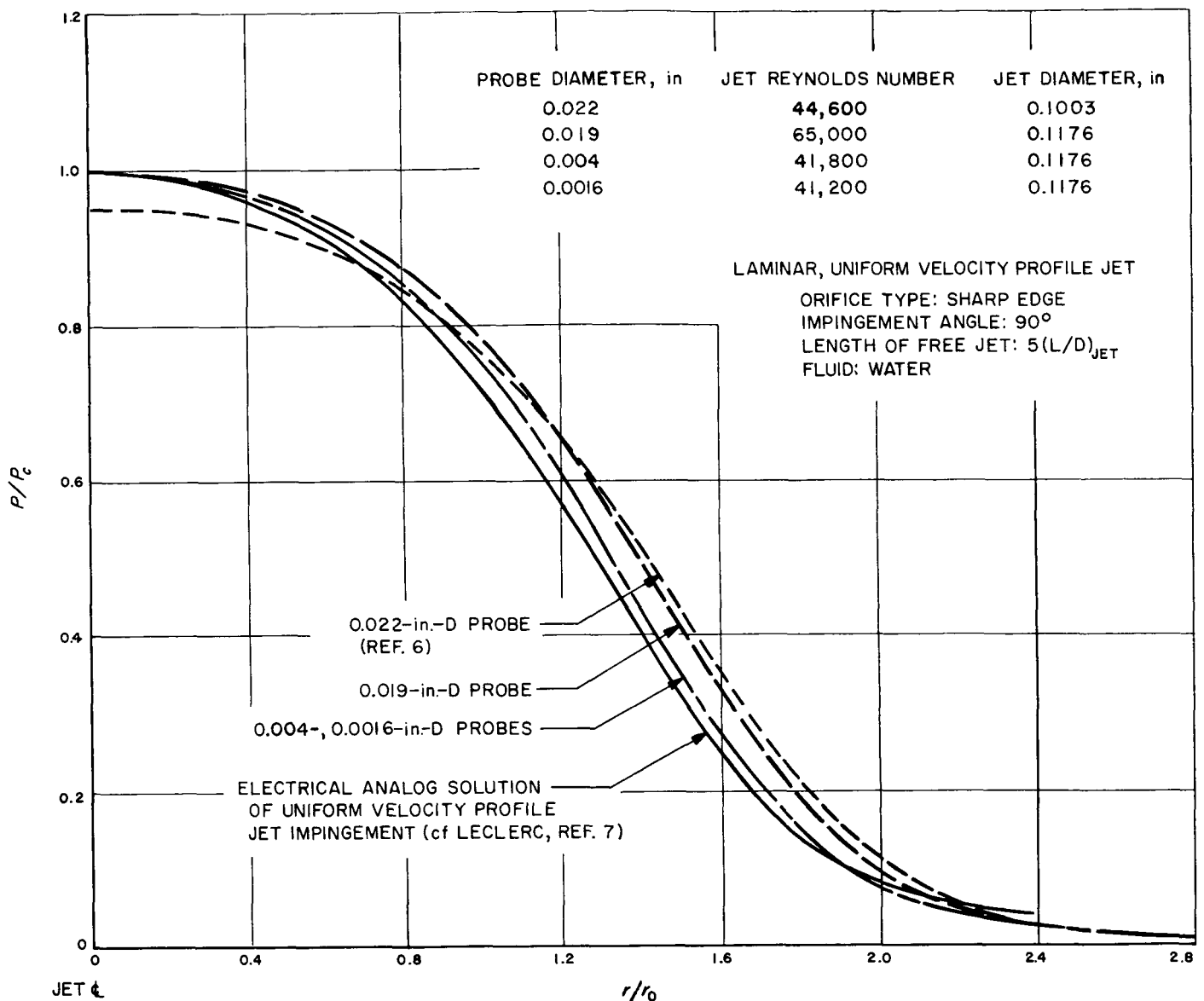


Fig. 5. Pressure distribution produced by a laminar, uniform velocity profile jet impinging on a flat plate

evaluated. Percentage differences between the two force determinations are indicated for each probe-jet configuration.

### B. Analysis of Data

Consider for the moment those data presented in Table 4 which were obtained by using a laminar, uniform velocity profile jet. Summarized in that listing are the results of two independent determinations of the force produced by the impingement of the jet upon a flat plate; one measurement was directly obtained from a thrust balance and the other by integrating the net measured pressure force on the plate. Note that, in the case

of the 0.019-in.-D probe, the difference between the two readings was 9.9% while with the two smaller probes the difference was reduced to approximately 1.0%. It should be pointed out, at this juncture, that the thrust balance method produced data which, in every case, correlated within  $\pm 0.6\%$  with the momentum calculable from weight flow measurements obtained with the laminar, uniform velocity profile jet. Hence, the results obtained from this apparatus may be considered, within the accuracy limits stated, to be representative of the reaction force produced by the impingement of the jet. Therefore, the implication that can be readily drawn from these results is clear, namely that pressure sensing

**Table 2. Pressure distribution produced by a laminar, uniform velocity profile jet impinging on a flat plate<sup>a</sup>**

$r/r_0$	$P/P_0$		
	Probe hole diameter 0.019 in.	Probe hole diameter 0.004 in.	Probe hole diameter 0.0016 in.
	Jet Reynolds number		
	65,000	41,800	41,200
0	0.994	1.000	0.999
0.170	0.993	0.996	0.998
0.340	0.981	0.980	0.978
0.510	0.954	0.948	0.949
0.680	0.912	0.902	0.901
0.850	0.851	0.833	0.833
1.020	0.774	0.740	0.740
1.190	0.664	0.619	0.620
1.360	0.531	0.473	0.475
1.530	0.388	0.332	0.335
1.701	0.254	0.210	0.207
1.871	0.150	0.121	0.119
2.041	0.081	0.069	0.067
2.381	0.026	0.024	0.022
2.721	0.009	0.013	0.011
<sup>a</sup> Jet diameter = 0.1176 in. Orifice: sharp edge Impingement angle = 90° Length of free jet = 5.00 (L/D) <sub>jet</sub> Fluid: water			

holes that are large relative to the diameter of the jet can lead to erroneous pressure measurements. This hypothesis is further substantiated by examining the data given in Fig. 5. Illustrated therein are the variations observed in the pressure distribution data caused by use of different sized probes. An improved correspondence between the theoretical results of LeClerc and the experimental data can be seen when the smaller probes were used.

These results are not completely unexpected in light of the earlier work of the other investigators cited. Nevertheless, it is gratifying to note the relatively good agreement between the theoretical and experimental results obtained in this case. It is curious that no further change in the measured pressure distribution was observed when the probe hole diameter was reduced from 0.004 to 0.0016 in. This is apparently indicative of a lessening of

the streamline curvature in the vicinity of the hole as the diameter was diminished until the deviation between the "actual" pressure and the empirically determined pressure became immeasurable.

A similar evaluation was performed for the data, given in Table 4, which was obtained by using the fully developed turbulent velocity profile jet. Equivalent findings were noted in the force comparisons, and Fig. 6 reveals the corresponding change in the measured pressure distributions. Unfortunately, in this case, there is no theoretical model for this flow configuration and LeClerc's data is included solely for reference. It is observed, however, that the centerline stagnation pressure ratio for the case of the 0.0016-in.-D probe is 1.478 which is the approximate value to be expected if the jet has a fully developed turbulent velocity profile (cf. Fig. 16 in Ref. 6).

**Table 3. Pressure distribution produced by a fully developed turbulent velocity profile jet impinging on a flat plate<sup>a</sup>**

$r/r_0$	$P/P_0$	
	Probe hole diameter 0.019 in.	Probe hole diameter 0.0016 in.
	Jet Reynolds number	
	65,100	49,800
0	1.465	1.478
0.166	1.456	1.462
0.332	1.411	1.405
0.498	1.325	1.302
0.664	1.219	1.181
0.830	1.073	1.002
0.996	0.902	0.840
1.162	0.715	0.656
1.328	0.514	0.478
1.494	0.329	0.316
1.660	0.174	0.178
1.826	0.083	0.110
1.992	0.028	0.078
2.324		0.044
2.656		0.022
<sup>a</sup> Jet diameter = 0.1205 in. Orifice = 200 (L/D) <sub>jet</sub> Impingement angle = 90° Length of free jet = 4.00 (L/D) <sub>jet</sub> Fluid: water		

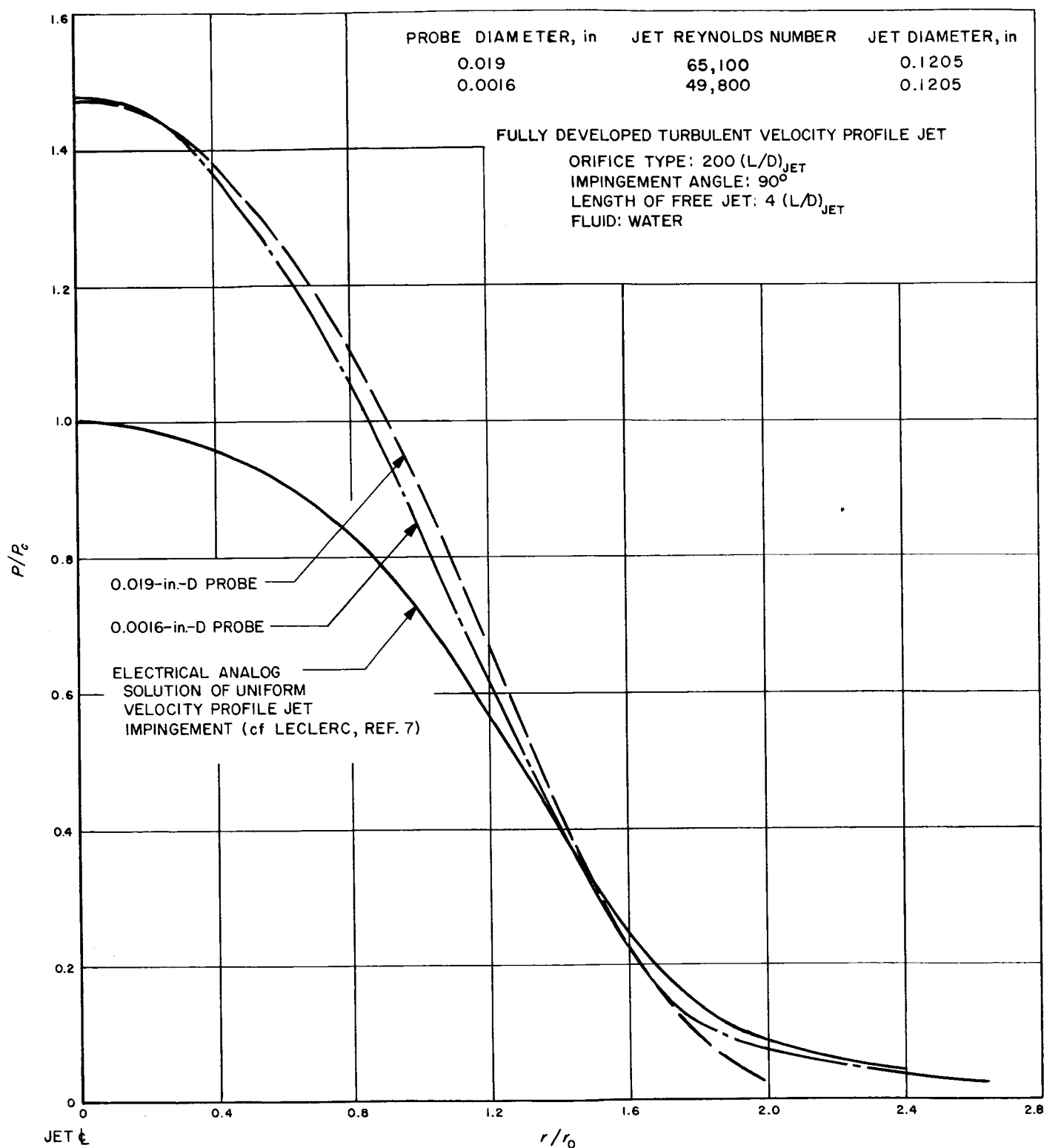


Fig. 6. Pressure distribution produced by a fully developed turbulent velocity profile jet impinging on a flat plate

**Table 4. Reaction force produced by jet impingement on a flat plate as determined by the thrust balance and by integration of net measured pressure force on the plate**

Type of Jet	Jet diameter, in.	Jet Reynolds number	Probe hole size, in.	Directly measured reaction force, g	Integrated pressure force, g	Difference in force measurements, %
Laminar, uniform velocity profile	0.1176	65,000	0.019	327.8	360.2	+9.9
	0.1176	41,800	0.004	134.9	136.2	+0.9
	0.1176	41,200	0.0016	130.8	132.1	+1.0
Fully developed turbulent velocity profile	0.1205	65,100	0.019	326.8	358.4	+9.7
	0.1205	49,800	0.0016	191.4	193.2	+0.9

Of significance in the new data presented in Fig. 5 is the apparent attainment of a more nearly uniform velocity profile jet as evidenced by the centerline stagnation pressure ratio of very nearly 1.00 in every case. It is not clear why the earlier data presented does not show a similar result since the effect of hole size, *per se*, is not overwhelmingly important when measuring stagnation pressures. This is clearly shown by the other stagnation pressure measurements indicated in Fig. 5 and 6. Hence, unless a gross error in the data reduction procedures is the reason, which is unlikely, the probable cause of the discrepancy in the data of Ref. 6 might be traced to the non-quiescent nature of the flow system used.

It would be well to be able to generalize the results obtained, but with the limited data on hand this is not possible. Suffice it to say that the hole size used in the

flat-plate dynamic-head probe should be as small as required to make its presence in the pressure field undetectable. The upper limit on the hole size which satisfies this criterion for a given flow geometry is not known, but a hole size which is approximately 4% of the jet diameter has been shown to be satisfactory in meeting this requirement.

The discrepancy of approximately 1% between the force determinations is attributable to experimental errors. The pressure readings were accurate within  $\pm 0.3\%$ . As stated earlier, the weight flow accuracy was  $\pm 0.4\%$  and the thrust reading was accurate within  $\pm 0.6\%$  (assuming the flow to be completely turned  $90^\circ$  by the impingement process).

A brief summary of the data presented in this Report was originally given in Ref. 8.

## V. SUMMARY

Results and conclusions based on the preceding Sections of this Report are as follows:

1. The hole size used in the flat-plate dynamic-head probe has been found to be a significant factor affecting the accuracy of the pressure measurements obtained with the probe.
2. Pressure distributions closely matching the theoretical data of LeClerc have been obtained with 0.004- and 0.0016-in.-D probes.
3. A ratio of the probe hole diameter to the jet diameter of 0.04 has been shown to be sufficient to eliminate probe hole size effects from influencing the measured pressure distribution.

## NOMENCLATURE

$D$	diameter
$L$	length
$N_R$	Reynolds number
$P$	static pressure at a given location
$P_c$	stagnation pressure of jet having a uniform velocity profile
$R$	radius to point where measured pressure on plate is zero
$r$	radius to point of measurement
$r_0$	radius of free jet
$V$	velocity

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